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Optimization Methods and Design Strategies for Topological Calculation of Spatial Structure of Landscape Architecture Green Space System

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Abstract Landscape greening system plays an important role in promoting urban construction, improving ecological environment and improving residents' quality of life. This paper introduces the complex network theory, constructs a network model of landscape green space system, and takes the correlation, connectivity, robustness and basic static statistical characteristics of the network as the indexes of landscape green space system to provide a method for the topological analysis of the spatial structure of landscape green space system. Taking Ordos City, Inner Mongolia, China, as the study area, the topological analysis of the spatial structure of landscape green space system is carried out, and then in response to the optimization demand, a multi-objective optimization model for the layout of urban parks is constructed based on the NSGA-II algorithm, which is used as the basis for the screening of candidate points of landscape green space to be constructed under planning. Using the model of this paper to optimize the spatial structure of Ordos City landscape garden green space system, most of its node degree, important nodes and connectivity are improved significantly, and the number of network attack nodes reaches 300 after optimization, and the connectivity robustness is still around 0.2.

Index Terms complex network model, topology calculation, NSGA-II algorithm, landscape green space

I. Introduction

Urban green space system is an important spatial guarantee to realize the coordinated development of urbanization construction and urban habitat quality enhancement, which enhances the spatial environment of urban built-up areas and at the same time, provides residents with space for rest and recreation and enjoyment of nature [1]-[3]. However, with the rapid development of urbanization, the continuous expansion of urban land has gradually eroded the green space, and the rapid differentiation of urban society has also made the equity of green space services increasingly prominent [4], [5]. Therefore, the planning process of the urban green space system has received more and more attention, and the focus is not only limited to the quantity and scale of the green space itself, but also the rationality of its spatial distribution, the convenience and fairness of its use by the residents have also become an important issue facing urban planning [6]-[8].

When discussing the internal spatial structure of urban planning and its nodes, topological computational optimization methods can be used to quantitatively analyze the social activities of urban residents [9], [10]. After rationally studying the topological principle, human perception is integrated into the planning of urban landscape green space system, not only studying the urban space, but also combining human activities with the spatial form of the city, and this urban spatial profiling method can better combine with its deep-seated essential needs [11]-[14]. In conclusion, the topological calculation optimization method defines the method of spatial awareness as group construction, and combined with spatial construction, it can better establish a complete spatial cognitive bridge and promote the scientific and reasonable design of urban green space system [15]-[18].

In order to realize the topological analysis of the spatial structure of landscape green space system, this paper combines the principle of complex network and builds up a complex network model. Through the complex network model, the basic static statistical characteristics of the network such as degree and degree distribution, average path length, clustering coefficient, etc. are calculated, the clustering coefficient distribution function is used to obtain the distribution of clustering coefficients, the node mediator is used to reflect the importance of the ecological nodes, the degree of connectivity of the complex network is defined, and the evaluation method of the structural robustness is proposed. Selecting Ordos City, Inner Mongolia, China, as the study area, the topological analysis of the spatial structure based on the complex network proves the demand and necessity of the optimization of the spatial structure of the green space system of landscape gardens. Facing the optimization demand of the spatial structure of landscape green space system, a multi-objective optimization model of the spatial structure of landscape green space system is constructed based on the NSGA-II algorithm, and the optimal layout of the park landscape green space system planning satisfying the set of objective solutions is screened out. The model of this paper is used to optimize the spatial structure of landscape green space system in Ordos City, and the performance and effect of the optimization are discussed in terms of the network topology and robustness before and after the optimization.

II. Topological analysis of the spatial structure of the landscape green space system

With the continuous expansion of urban green space and the gradual improvement of residents' requirements for landscape quality, the construction of landscape garden green space system is an important guarantee for maintaining urban ecological security during the construction and maintenance of urban green space plant landscape. Landscape garden green space system has a complex structure in space, and there is a complex relationship between each layer of landscape garden green space system. In this paper, we will utilize the complex network theory to topologically analyze the spatial structure of landscape green space system with Ordos City, Inner Mongolia, China, as a typical study area.

II. A. Indicators for evaluating space structure

The connectivity and complexity of a landscape green space system can be evaluated through the network measurement indexes of graph theory, and the structure analysis of the landscape green space system can effectively explore the internal structure of the landscape green space system. α index, β index, γ index and other network structure indexes are used to study the level of closure and connectivity of the hierarchical landscape green space system. The α index is used to describe the degree of possible loops in the network, and the larger the value indicates the smoother material circulation and circulation of the network: the B index refers to the average number of connecting lines of each node in the network, which can measure the complexity of the network; the γ index reflects the degree of connectivity of the network, and the formula is:

$$\alpha = \frac{l - v + 1}{2v - 5} \tag{1}$$

$$\beta = \frac{l}{v} \tag{2}$$

$$\gamma = \frac{l}{l_{max}} = \frac{l}{3(v-2)} \tag{3}$$

where: l is the number of corridors; v is the number of nodes; d is the length of the corridor.

II. B. Complex network modeling

II. B. 1) Basic static statistical characteristics of the network

1) Degree and degree distribution

In a landscape green space system, the degree of an ecological node is the number of corridors connected to this ecological node, and the greater the degree of the node indicates the higher importance of this ecological node. The greater the status of this ecological node in the landscape green space system. The average degree of the network is an important indicator of the structure of a landscape green space system, and the average degree of the network is the average of the degree of each ecological node in the network. The calculation formula is as follows:

$$\langle k \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i \tag{4}$$

where, $\langle k \rangle$ represents the average degree of the network and N represents the number of nodes.

2) Average path length

After summing the number of edges on the shortest path of any two nodes in the network, the average value is taken to get the average path length of the complex landscape green space system, and the formula is as follows:

$$L = \frac{1}{c_N^2}\Sigma_{1\le i\le j\le N} d_{ij} \tag{5}$$

In complex network theory, an algorithm for breadth-first search of time magnitude O(MN) is used to determine a network containing N nodes and M edges [19].

3) Clustering coefficients [20].

In the hierarchical landscape green space system, two nodes connected to the unified ecological node are not connected to each other, but there is a certain relationship between the two nodes, this property is called the clustering property of the network. The clustering coefficient c_i is defined as the ratio between the number of edges E_i that actually exist between the k_i neighboring nodes of node v_i and the total number of possible edges $C_{k_i}^2$, which is calculated by the formula:

$$C_i = \frac{E_i}{c_{k_i}^2} \tag{6}$$

where E_i represents the number of actual ecological corridors connected between an ecological node and its neighboring nodes. $C_{k_i}^2$ represents the total number of possible edges connecting the ecological node to its neighboring nodes.

The average clustering coefficient C is the average of all the ecological node clustering coefficients with the formula:

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{7}$$

The average clustering coefficients of complex landscape green space systems are 0 to 1.

II. B. 2) Relevance of landscape green space systems

1) Degree-degree correlation based on Pearson correlation coefficient [21]

The Pearson correlation coefficient r for the degree of a landscape green space system is calculated as:

$$r = \frac{M^{-1}\sum_{e_{ij}\in E} k_i k_j - \left[M^{-1}\sum_{e_{ij}\in E2}\frac{1}{2}(k_i + k_j)\right]^2}{M^{-1}\sum_{e_{ij}\in E2}\frac{1}{2}(k_i^2 + k_j^2) - \left[M^{-1}\sum_{e_{ij}\in E2}\frac{1}{2}(k_i + k_j)\right]^2} \tag{8}$$

where k_i, k_j represents the degree of the two ecological individual nodes v_i and v_j, respectively, connecting ecological corridor e_{ij}; M is the total number of ecological corridors in the network; and E is the set of all ecological corridors.

2) Distribution of clustering coefficients and cluster-degree correlation

Similar to the concept of degree-degree correlation of the network, there exists a certain intrinsic connection between the clustering coefficients and the degree of a landscape green space system, i.e., the cluster-degree correlation. The relationship between local clustering coefficients $C(k)$ and k is the main concern in the calculation of cluster-degree correlation.

The number of nodes of landscape green space system is the number of ecological nodes passed by the shortest ecological corridor path between any two ecological nodes in the landscape green space system, and the number of ecological nodes can be used to reflect the importance of ecological nodes in the landscape green space system. The median of ecological nodes B_i is calculated by the formula:

$$B_i = \sum_{1\le j\le l\le N} [n_{jl}(i)/n_{jl}] \tag{9}$$

where n_{jl} is the number of shortest ecological corridors between ecological nodes v_j and v_i; $n_{jl}(i)$ is the number of shortest ecological corridor paths between ecological nodes v_j and v_i passing through ecological node v_i; and N is the total number of ecological nodes in the green space system of landscape garden.

II. B. 3) Connectivity of the landscape green space system

1) Kernel of landscape green space system

The kernel of a landscape green space system is the number of ecological nodes and their interconnected ecological corridors with degree less than k that are continuously removed, and the number of ecological nodes in the connected subgraphs eventually remaining is the kernel number. If an ecological node belongs to the k-nucleus, but does not belong to the (k+1)-nucleus, the nucleus number of this ecological node is k, and the nucleus number of this landscape green space system is also k. Through the analysis of the k-nucleus statistics, it is found that the complex network gradually tends to the core of the region, and the more the nucleus is located in the center, the stronger the connectivity is.

2) The connectivity of nodes

The connectivity degree of the network nodes mainly reflects the degree of connectivity of the landscape green space system. The connectivity degree $k(G)$ of a connected complex network G is defined as:

$$k(G) = \min_{s \in V} \{|S|, \omega(G-S) \geq 2 \text{ or } G\text{-}S \text{ is a trivial graph}\} \tag{10}$$

where V is a combination of ecological nodes of the landscape green space system G; S is a true subset of V; and $\omega(G-S)$ is the number of connected branches of the subgraph obtained by deleting the set of ecological nodes S from the landscape green space system G.

II. B. 4) Robustness of landscaped green space systems

After the spatial structure of a landscape green space system has been damaged, the ability of a potential landscape green space system to recover is the recovery robustness. The formula for structural robustness is:

$$R = \frac{c}{(N - N_r)} \tag{11}$$

where N represents the number of ecological nodes in the initial potential landscape green space system; N_τ represents the number of nodes removed from the landscape green space system; c represents the number of sub-networks with the highest number of ecological nodes in the sub-networks in the hierarchical landscape green space system when the nodes are removed. For ecological nodes and ecological corridors, the formulas for restoration robustness are respectively:

$$D = 1 - \left[\frac{(N_r - N_d)}{N}\right] \tag{12}$$

$$E = 1 - \left[\frac{(M_r - M_e)}{M}\right] \tag{13}$$

where D represents the node recovery robustness metric; E represents the edge recovery robustness metric; N_d represents the number of nodes recovered by some strategy; M represents the number of edges in the initial network: M_r represents the number of edges removed from the network; M_e represents the number of edges recovered by some strategy.

II. C.Topological analysis of spatial structures based on complex networks

In this section, the complex network model will be used as a research method to topologically analyze the spatial structure of landscape green space system.

II. C. 1) Basic static structure analysis

The interconnection between each landscape green space relies on the ecological node, which is in a key position in the landscape green space system. Considering ecological corridors as edges connecting nodes in the landscape green space system, and then combining the complex network, the degree of landscape green space system is introduced to characterize the number of corridors connecting an ecological node. The larger the degree value, the more ecological corridors connecting the node, the higher the accessibility and the greater the importance of the node. The degree distribution of the landscape green space system is shown in Figure 1.

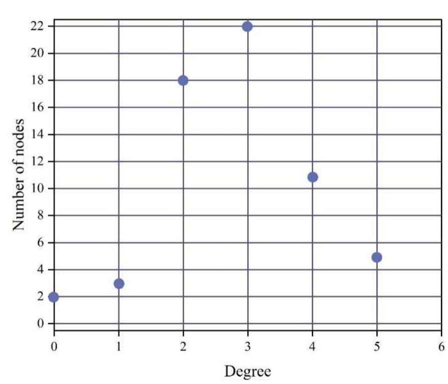


Figure 1: Degree distribution

The average degree of the network is of great significance to the ecological network structure, which can visualize the interrelationship between nodes. In this paper, a total of 53 ecological nodes are identified, and the average degree of the network is 2.949, which indicates that there is a connectivity relationship between one node and three other nodes in the ecological network. As can be seen from the figure, there are two nodes with degree 0 in the ecological network, which means that these two ecological nodes are in an isolated state, and the whole landscape green space system is not a completely connected state. There are three nodes with degree 1 in the network, accounting for 5.66% of the total ecological nodes, 18 nodes with degree 2, accounting for 34% of the total nodes, and the largest number of nodes with degree 3, 22 nodes, accounting for 41.51% of the total nodes. The maximum value of degree for the whole network is 5 with 5 nodes.

II. C. 2) Node Importance Analysis

The edges of a complex network mainly refer to the connection relationship between ecological nodes, so this section will focus on the importance of nodes using the centrality of node median of landscape green space system. Node median is the proportion of the shortest path through a node to the shortest path in the whole network. In the complex network, there exists a kind of node degree value is low, but it connects two important patches, if the point is removed, the overall connectivity of the landscape green space system will be sharply reduced, so this kind of node is also equally important, so the node meso-centrality is equally important relative to the node degree value in the study. The distribution of the node meson number of the landscape garden green space system is shown in Fig. 2. As can be seen from the figure, the node degree value of the whole landscape garden green space system is generally low. Among the 53 ecological nodes, there are 24 ecological nodes lower than 50, accounting for almost 1/2 of the total number of nodes, and the highest ecological node median is 485, only one, indicating that most of the nodes in the landscape garden green space system are of low importance, and the network is more heterogeneous.

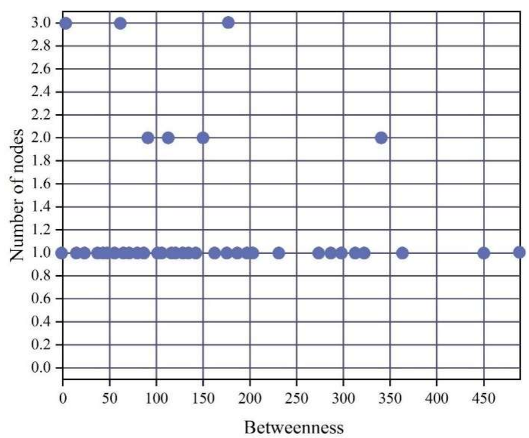


Figure 2: Distribution of node betweenness

II. C. 3) Clustering coefficient analysis

The clustering coefficient indicates the degree of aggregation among ecological nodes. In practice, the possibility of establishing this organizational relationship between nodes is greater than the probability of setting up one of its arbitrary relationships, and this interrelationship can be quantitatively expressed by the clustering coefficient, and the higher the clustering coefficient is, the more frequent the connection between nodes in its neighborhood is. The article uses Gephi software to calculate that the average clustering coefficient of landscape green space system is 0.112, and this lower clustering coefficient also indicates that landscape green space system has no small world characteristics. The distribution of clustering coefficient is shown in Figure 3. As can be seen in the figure, there are more nodes with a clustering coefficient of 0 in the landscape green space system, amounting to 32 nodes, accounting for 60.4% of the total number of nodes, and they have no clustering characteristics and are more obviously dispersed. Secondly, nodes with a clustering coefficient of 0.45 accounted for 10 nodes, and nodes with a clustering coefficient of 1 accounted for only 6 nodes. The large difference in the values of the clustering coefficients indicates that the heterogeneity of the landscape green space system is strong, and the distribution of nodes and corridors is relatively dense in some areas, while it is sparse in some regions, and this kind of landscape green space system tends to have a low robustness when it is subject to malicious attacks, and the spatial structure of the landscape green space system needs to be optimized further, to reduce the heterogeneity of the network, and to promote the landscape green space system's landscape Circulation.

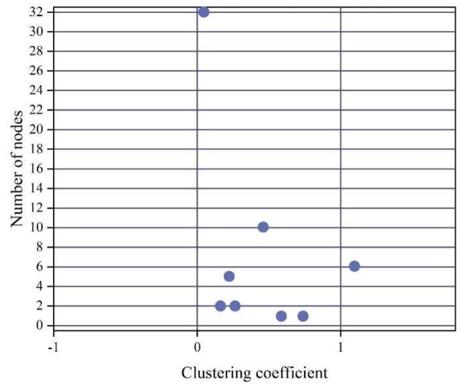


Figure 3: Clustering coefficient

III. Multi-objective optimization model for the spatial structure of the green space system in landscape gardens

In the previous chapter, this paper analyzed the spatial structure of landscape green space system topologically through complex network theory. The topological structure analysis shows that the nodes of the landscape garden green space system have lower importance and aggregation, and at the same time, they all show more obvious heterogeneity, the distribution of important nodes is less, and the degree value, median value and clustering coefficient of the ecological nodes are generally lower, which need to be further optimized.

In this chapter, NSGA-II algorithm will be introduced, on the basis of which a multi-objective optimization model of the spatial structure of landscape green space system will be constructed, and the optimal layout of the spatial structure planning of landscape green space system that satisfies the objective solution set will be screened out, so as to optimize the spatial structure of landscape green space system [22].

III. A. Screening of Candidate Sites for Planning of Landscape Green Space to be Constructed

Landscape garden green space is to supplement the inadequacy of the current layout of urban park green space and maximize the social justice of park green space. With reference to the green space system planning, combined with the satellite image map for field investigation and research, the planned urban parks and squares, as well as the subsidiary green spaces and protective green spaces that are free of safety hazards and have the potential to provide residents with recreational and open space, are selected as candidates for scenic garden green spaces.

As a basic component of urban ecosystem and an important space for providing on-site interaction activities, the selection of the optimal location of the landscape green space shall follow:

1) Social justice: everyone can enjoy the services provided by the park green space, and the service level of the park green space is appropriately inclined to the disadvantaged groups.

2) Spatial accessibility: the total weighted level of park green space accessibility is the highest, and the use efficiency of park green space is maximized.

3) Economy of construction: It is required to control the cost and reasonably construct the park green space under the premise of meeting the first two points.

III. B. Construction of multi-objective optimization model for urban park layout

Based on the theoretical study of social justice and the characteristics of green space selection in landscape gardens, the multi-objective decision-making model and objective function are proposed as follows:

$$\max f_{availability} = \sum_{j=1}^{n}\sum_{i=1}^{m} X_i \cdot D_{ij} \cdot Y_{ij} \tag{14}$$

$$\max f_{pop} = \sum_{i=1}^{m}\sum_{j=1}^{n} P_j \cdot X_i \cdot D_{ij} \cdot Y_{ij} \tag{15}$$

$$\max f_{pop} = \sum_{i=1}^{m}\sum_{k=1}^{w} P_j \cdot X_i \cdot D_{ij} \cdot Y_{ij} \cdot K_j \tag{16}$$

$$\max f_{accessibility} = \sum_{i=1}^{m} \frac{S_i}{\sum_{j=1}^{n} P_j \cdot D_{ij}} \cdot X_i \cdot Y_{ij} \tag{17}$$

$$\min f_{area} = \sum_{i=1}^{m} S_i \times X_i \tag{18}$$

Eq. (14) represents maximizing the availability of the selected landscaped green space; Eq. (15) represents maximizing the population served by the selected residential area; Eq. (16) represents maximizing the population served by the selected low-income residential area; Eq. (17) represents maximizing the accessibility of the selected landscaped green space; and Eq. (18) represents minimizing the area of the selected landscaped green space.

IV. Analysis of the effect of optimizing the spatial structure of the green space system in landscape gardens

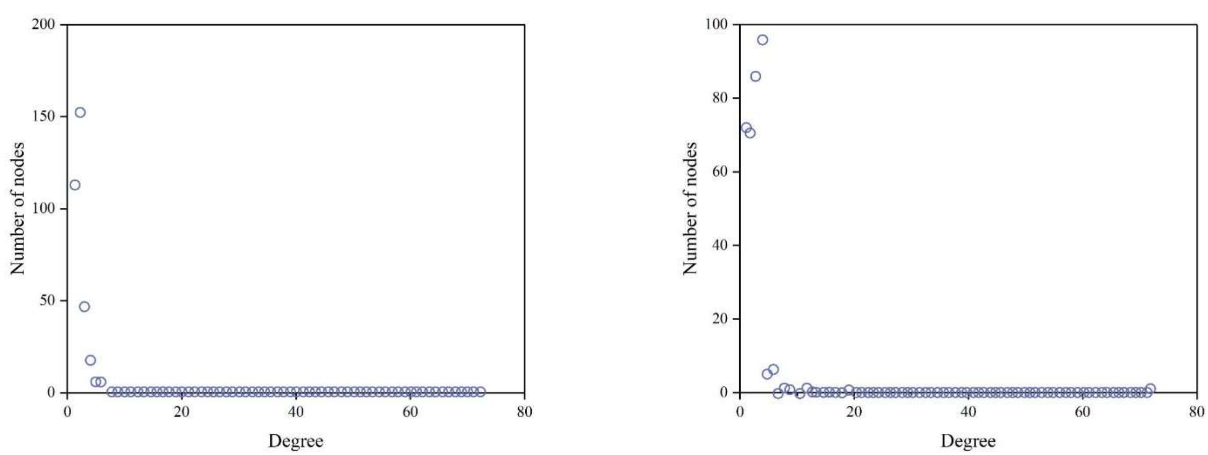
In this chapter, the multi-objective optimization model of the spatial structure of landscape green space system proposed in this paper will be used to optimize the spatial structure of landscape green space system in Ordos City.

This paper will analyze the optimization effect of the landscape garden green space system in Ordos City from the aspects of network topology and robustness before and after optimization, taking the spatial center of mass of the ecological source and the weak ecological nodes together as the nodes of the complex ecological network, and the ecological corridors as the edges of the complex ecological network, and expressing them with the adjacency matrix.

IV. A. Comparative analysis of network topologies

IV. A. 1) Nodality

Before and after the optimization, the degree distribution of the landscape green space system is specifically shown in Fig. 4, Figs. (a) and (b) correspond to the pre-optimization and post-optimization, respectively. From the figure, we can see that before and after the optimization of the network do not exist nodes with degree 0, the degree distribution are also more obvious power law distribution characteristics, but after the optimization of the network has a slight Poisson distribution characteristics, which indicates that after the optimization of the network scalelessness characteristics are still stronger than the uniformity characteristics but the degree of mitigation. The nodes with degree 1 and 2 are reduced, and the degree of the highest number of nodes increases from 2 to 4, and the maximum value of the degree is 72, which indicates that most of the nodes' degree is improved, and the network connectivity is increased.

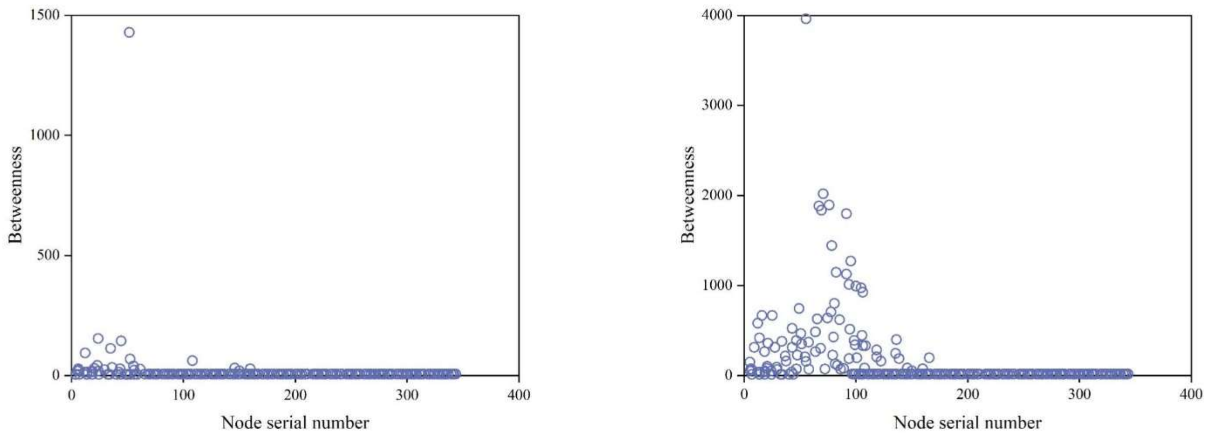


(a) Before optimization (b) After optimization

Figure 4: Node degree

IV. A. 2) Number of nodes

The node mediator number of the landscape green space system before and after optimization is specifically shown in Fig. 5, Figs. (a) and (b) correspond to the pre-optimization and post-optimization, respectively. In the pre-optimization network, 77.78% of the nodes have a median of 0, except for the median of the 54th patch, which is 1419, and the rest of the nodes have a median of less than 150; while after optimization, the nodes with a median of 0 accounted for only 55.56% of the network, the nodes with a median of more than 150 accounted for 21.64% of the total number of nodes, and there are 14 with a median of more than 1,000, and the largest number of medians was in the 54th patch, which was 3,986, showing that more important nodes in the network after optimization, the importance increases and the network is more stable.

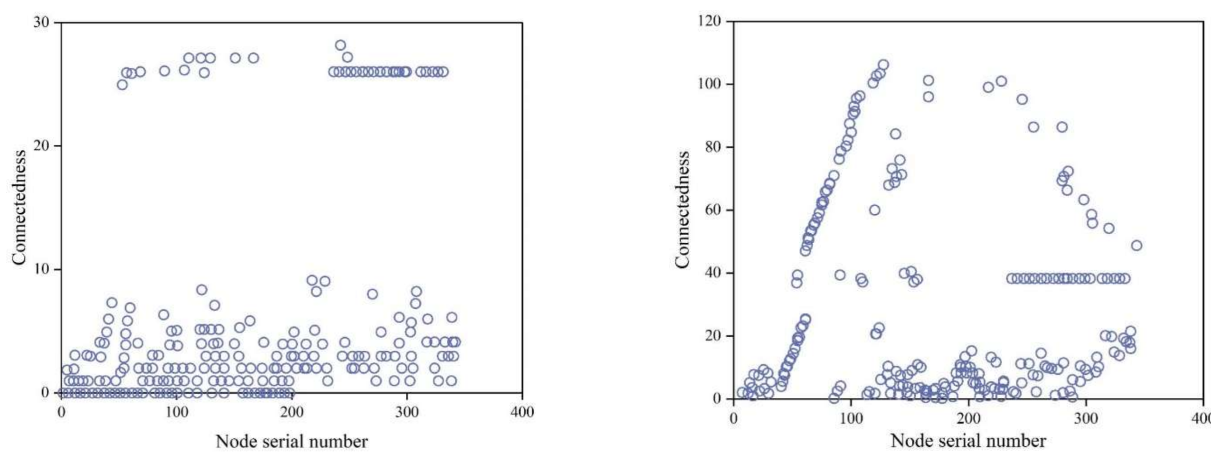


(a) Before optimization (b) After optimization

Figure 5: Node betweenness

IV. A. 3) Connectivity

The change of connectivity of the landscape green space system is specifically shown in Fig. 6, and Figs. (a) and (b) correspond to pre-optimization and post-optimization, respectively. The connectivity of 83.04% of the ecological nodes in the pre-optimization network is lower than 10, and the rest of the nodes have connectivity between 25 and 28; while only 64.04% of the nodes in the post-optimization network have connectivity lower than 25, and the rest of the nodes have connectivity higher than 35, with the highest of 106, which indicates that the connectivity of the network is significantly enhanced after optimization, and the ecological flow of the network is far more unimpeded than that of the pre-optimization.

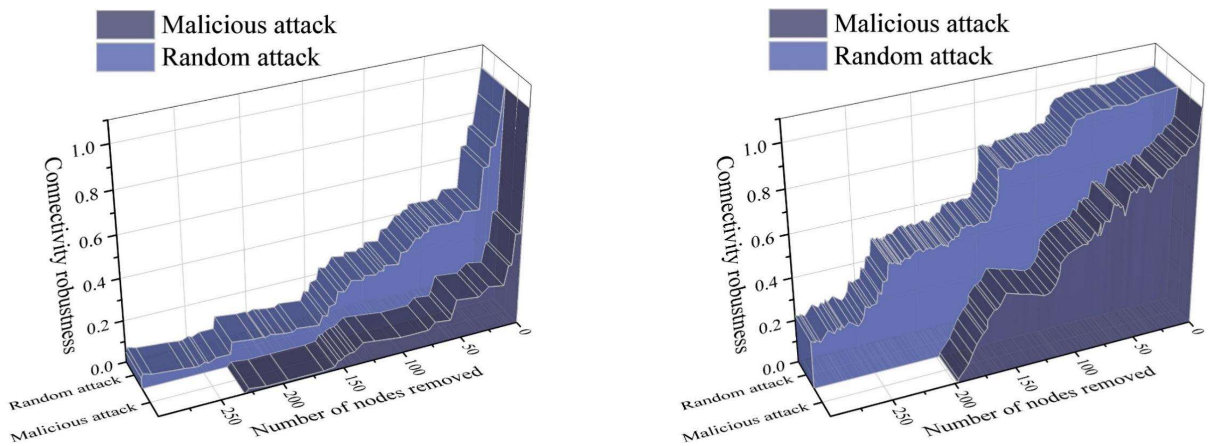


(a) optimization (b) After optimization

Figure 6: Connectedness

IV. B. Comparative Robustness Analysis

We use two strategies, malicious and random, to attack the landscape system before and after optimization, and analyze the change of the robustness of the system's network connection with the increase of the attack strength. The robustness of the landscape green space system before and after optimization is shown in Fig. 7, with Figs. (a) and (b) corresponding to pre-optimization and post-optimization, respectively. The results show that the initial connectivity robustness of the network is only 0.97 before optimization and increases to 1 after optimization, indicating that the network structure is stable and the connectivity is strong after optimization. As the attack size increases, the connectivity of the network decreases rapidly, but in general, random attacks are better than malicious attacks, and the optimized network is in a better situation. Under malicious attacks, the pre-optimization network has already experienced the phenomenon of "emergence" when the network removes to the second node, and the connectivity robustness of the network decreases sharply to 0.45, while it decreases to 0.89 after optimization. The connection robustness of the pre-optimization network drops to 0.2 when the number of removed nodes increases to 14, while the post-optimization network attacks 178 nodes. The connection robustness is almost completely lost when 159 nodes are removed for the pre-optimization network and 199 nodes are removed for the post-optimization network. Under random attacks, the connection robustness of the pre-optimization network plummets to 0.48 when 24 nodes are removed, while the network connectivity is still fully recovered when the post-optimization network is attacked up to 20 nodes. The connection robustness decreases to below 0.1 when the number of nodes removed from the pre-optimization network reaches 156, and the connection robustness remains around 0.2 when the number of nodes attacked by the post-optimization network reaches 300. It shows that the optimized landscape ecological network has a very substantial improvement in connectivity and stability because of the increase in corridors and node degree.



(a)Before optimization (b)After optimization

Figure 7: Robustness

V. Conclusion

Based on the complex network model, this paper proposes a topological analysis method for the spatial structure of landscape green space system. Ordos City, Inner Mongolia, China, is taken as the study area, and the topological analysis of the spatial structure of its landscape green space system is carried out. In the basic static structure, the average degree of the network of the landscape green space system is 2.949, and there are two ecological nodes with degree 0 and in an isolated state, and the number of nodes with degree 2 and 3 is the largest, with 18 and 22 nodes, accounting for 34% and 41.51% of the total nodes, respectively. The whole landscape green space system is in a state that is not completely connected. The node median value of the whole landscape green space system is generally low, and the average clustering coefficient is a low 0.112, and the values of the clustering coefficients differ greatly, showing strong heterogeneity. Comprehensive topological analysis results show that the spatial structure of the landscape green space system still needs to be further optimized.

Aiming at the optimization demand of the spatial structure of landscape green space system, this paper constructs a multi-objective optimization model of the spatial structure of landscape green space system based on NSGA-II algorithm, which provides ideas for the optimization of the spatial structure of landscape green space system. Using the spatial structure multi-objective optimization model in this paper, the landscape green space system in Ordos City is optimized, and its optimization effect is discussed from the aspects of network topology and robustness before and after optimization. In terms of network topology, the nodes with degrees 1 and 2 decrease and the degree of the highest number of nodes increases from 2 to 4, and the network connectivity increases. After optimization, only 55.56% of the nodes with the number of intermediaries of the network are 0, which is lower than the percentage of 77.78% before optimization, and the number of important nodes in the network increases after optimization, the importance increases, and the network is more stable. Compared with 83.04% of the ecological nodes with connectivity below 10 before optimization, 64.04% of the nodes in the landscape green space system after optimization have connectivity below 25, while the rest of the nodes have connectivity higher than 35, which is significantly enhanced, and the ecological flow of the network is far more smooth than before optimization. In terms of robustness, the initial connectivity robustness of the landscape green space system is only 0.97 before optimization, and it grows to 1 after optimization, with enhanced connectivity. In the face of malicious attacks, the network before and after optimization almost completely loses its connectivity robustness when 159 nodes are removed and 199 nodes are removed, respectively. The network connectivity robustness before optimization drops sharply to 0.48 when 24 nodes are removed, while the network connectivity is still fully recovered when the number of attacking nodes of the network is within 20 after optimization. Obviously, the multi-objective optimization model of spatial structure of landscape green space system proposed in this paper can effectively optimize the spatial structure of landscape green space system and enhance the connectivity and stability of landscape green space system.

References

[1] Şenik, B., & Uzun, O. (2022). A process approach to the open green space system planning. Landscape and Ecological Engineering, 18(2), 203-219.

[2] Zhou, Q., van den Bosch, C. C. K., Chen, Z., Wang, X., Zhu, L., Chen, J., ... & Dong, J. (2021). China's Green space system planning: Development, experiences, and characteristics. Urban Forestry & Urban Greening, 60, 127017.

[3] Semeraro, T., Scarano, A., Buccolieri, R., Santino, A., & Aarrevaara, E. (2021). Planning of urban green spaces: An ecological perspective on human benefits. Land, 10(2), 105.

[4] Anguluri, R., & Narayanan, P. (2017). Role of green space in urban planning: Outlook towards smart cities. Urban Forestry & Urban Greening, 25, 58-65.

[5] Daniels, B., Zaunbrecher, B. S., Paas, B., Ottermanns, R., Ziefle, M., & Roß-Nickoll, M. (2018). Assessment of urban green space structures and their quality from a multidimensional perspective. Science of the Total Environment, 615, 1364-1378.

[6] Halecki, W., Stachura, T., Fudała, W., Stec, A., & Kuboń, S. (2023). Assessment and planning of green spaces in urban parks: A review. Sustainable Cities and Society, 88, 104280.

[7] Lennon, M., Douglas, O., & Scott, M. (2017). Urban green space for health and well-being: developing an 'affordances' framework for planning and design. Journal of urban design, 22(6), 778-795.

[8] Irvine, K., Loc, H. H., Sovann, C., Suwanarit, A., Likitswat, F., Jindal, R., ... & De Wandeler, K. (2021). Bridging the form and function gap in urban green space design through environmental systems modeling. Journal of Water Management Modeling, 29.

[9] Moi, J., Chiesi, L., Chirici, G., Francini, S., Borghi, C., Costa, P., ... & Caldarelli, G. (2024). Urban topology and dynamics can assess the importance of green areas. Physical Review E, 110(6), 064128.

[10] Karimi, K. (2023). The configurational structures of social spaces: Space syntax and urban morphology in the context of analytical, evidence-based design. Land, 12(11), 2084.

[11] Eizenberg, E., Sasson, O., & Shilon, M. (2019). Urban morphology and qualitative topology: Open green spaces in high-rise residential developments. Urban Planning, 4(4), 73-85.

[12] Yu, X., Ma, S., Cheng, K., & Kyriakopoulos, G. L. (2020). An evaluation system for sustainable urban space development based in green urbanism principles—A case study based on the Qin-Ba mountain area in China. Sustainability, 12(14), 5703.

[13] Huang, B. X., Chiou, S. C., & Li, W. Y. (2021). Landscape pattern and ecological network structure in urban green space planning: A case study of Fuzhou city. Land, 10(8), 769.

[14] Qviström, M., Engström, A., Peinert, H., & Pries, J. (2025). Reconfiguring Green Space for the Compact City: Uncovering the Ontological Politics of Green Planning in a Deregulated Planning System. Nordic Journal of Urban Studies, 5(1), 1-17.

[15] Yang, J. (2024). Research on optimization strategies for urban park green space planning in Nanjing based on GIS from the perspectives of network analysis and Thiessen polygon theory. International Journal of Modern Physics C, 2441002.

[16] Mahmoud, A. H., & Omar, R. H. (2015). Planting design for urban parks: Space syntax as a landscape design assessment tool. Frontiers of Architectural Research, 4(1), 35-45.

[17] Xiu, N., Ignatieva, M., van den Bosch, C. K., Chai, Y., Wang, F., Cui, T., & Yang, F. (2017). A socio-ecological perspective of urban green networks: the Stockholm case. Urban ecosystems, 20, 729-742.

[18] Zhong, J., Li, Z., Sun, Z., Tian, Y., & Yang, F. (2020). The spatial equilibrium analysis of urban green space and human activity in Chengdu, China. Journal of Cleaner Production, 259, 120754.

[19] Jing Shi,Pei Ji Shi,Zi Yang Wang,Ya Wan,Fan Yuan Cheng & Li Rong Wang. (2024). [Ecological network optimization of Jiuquan City, Gansu, China based on complex network theory and circuit model]. Ying yong sheng tai xue bao = The journal of applied ecology,35(1),237-246.

[20] Zhaobo Zhang,Meizhu Li & Qi Zhang. (2024). A clustering coefficient structural entropy of complex networks. Physica A: Statistical Mechanics and its Applications,655,130170-130170.

[21] Rongbing Huang,Muhammad Farhan Hanif,Muhammad Kamran Siddiqui,Muhammad Faisal Hanif & Fikre Bogale Petros. (2024). Analyzing boron oxide networks through Shannon entropy and Pearson correlation coefficient. Scientific Reports,14(1),26552-26552.

[22] Yanni Shen & Jianjun Meng. (2025). A Study on Multi-Robot Task Allocation in Railway Scenarios Based on the Improved NSGA-II Algorithm. Sensors,25(4),1001-1001.